Tellus (1978), *30*, 358–364

Quantitative measurement of airborne sea-salt in the North Atlantic

By R. F. LOVETT, *Institute of Offshore Engineering, Heriot-Watt University, Edinburgh. Present affiliation Royal Naval School of Meteorology and Oceanography, Culdrose, Cornwall*

(Manuscript received March 1; in final form December 29, 1977)

ABSTRACT

Measurements of airborne sea-salt concentration were taken from North Atlantic weather ships during 11 voyages throughout the period September 1974 to July 1975. Total sea-salt concentrations were measured by air sampling through membrane filters. Sampling sites were at heights of 5, 10 and 15 metres above sea level. A total of 1821 aerosol samples were taken with an average of 57 samples per site per voyage.

An attempt has been made to correlate sea-salt concentration with wind speed and other meteorological factors. It was found that total sea-salt concentration could be represented as a function of wind speed by the equation $\ln \theta = 0.16u + 1.45$ (θ = sea-salt concentration in μg m^{-3} and u = wind speed in m s^{-1}) This shows good agreement with Blanchard and Syzdek's results. Observation of the time variation of sea-salt concentration and wind speed indicated residence times of the order of 12 to 24 hours. Attempts to distinguish dependence upon other meteorological parameters were not conclusive.

1. The wind dependence of sea-salt aerosol

There have been many attempts to correlate airborne sea-salt concentrations with wind speed but results have not been entirely consistent. The earliest data on the wind dependence of airborne sea-salt are from Woodcock's (1953) results taken at cloud levels over Hawaii. The slope of the regression line is approximately 0.16 (natural logarithms). Toba (1961) in a wind flume experiment obtained the following expression for the rate of production of particles:

$$F = e^{0.4u\ +\ \text{constant}}$$

In a later work Toba (1965) used data from Durbin and White (1961) and Woodcock (1953, 1957) to calculate the wind dependence of sea-salt production. The slope of the curves was 0.12. He ascribed the discrepancy between this result and his wind flume result as being due to the use of tap water in the laboratory experiment.

Tsunogai et al. (1972) measured sea-salt concentration from ships in the Pacific Ocean and obtained a wind dependence curve with a slope of 0.62. This is five times the value obtained by Toba. Tsunogai et al. reconcile their result with Toba's value on the basis of two assumptions: (1) the production of sea-salt particles $>10\,\mu$ radius or 10^{-8} g is more dependent on the wind velocity than is the production of small particles; (2) the residence time of the larger particles is so short that they contribute only to the weight concentration of sea-salt near the surface of the ocean. It is the opinion of the writer that Tsunogai's high result may be due to a contribution to the sea-salt aerosol as a result of the ship's motion. Apparently all samples were taken with the ships underway.

There is limited experimental field data on the wind dependence of sea-salt aerosol but results obtained by Woodcock are generally supported by other investigations and the evidence tends to favour Toba's value for the wind dependence slope. A literature survey reveals that there have been no long-term investigations of the sea-salt component of the marine aerosol. The aim of this investigation was to determine any possible seasonal variations, variations with meteorological factors, or variation with height above the sea surface of the sea-salt aerosol. To minimize the error scatter a large number of measurements were taken from weather ships at stations India, Juliet and Lima throughout

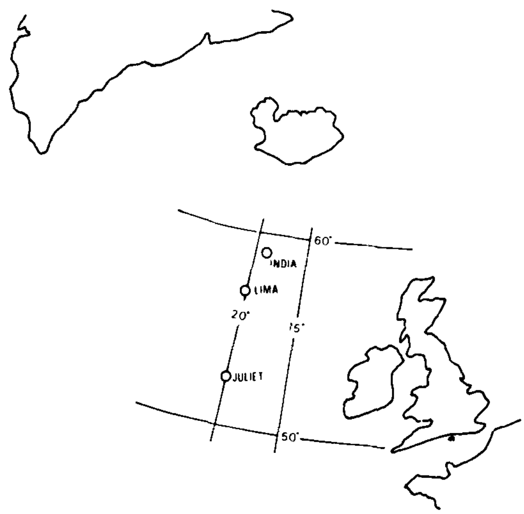

Fig. 1. Location of United Kingdom ocean weather stations.

the period August 1974 to July 1975. The location of the U.K. ocean weather stations is shown in Fig. 1 (stations India and Juliet are no longer used having been superseded by the one station Lima from July 75).

2. Measurement techniques

Both weather ships and oil rigs were considered as platforms but weather ships were chosen because they provide continuous and accurate meteorological data. Ships on passage were not considered as their wash is itself a source of sea-salt aerosol. When the weather ships reach their station (about three to four days out of harbour) they are stopped. The ships remain on a fixed heading relative to the wind direction due to a weathercock action. The wind blows from a direction slightly abaft of the beam (about 100° from the ships heading) so that the windward side is very exposed. The instruments were always fixed to the windward side and it is considered that good representative sampling was achieved in this way. The ships remain on station for about 25 days in each voyage. Membrane filter holders with isokinetic sampling heads of varying nozzle sizes were used to measure total sea-salt concentrations. Three filter holders were installed at three sites in each ship at heights of 5, 10 and 15 metres. The sampling instruments were clamped directly to the guard rail at the 5-metre site and to laboratory stands fixed to the bridge wing at the 10-metre site. Sampling at the 15-metre site was achieved by hoisting the instruments up a main mast halyard.

Suction through membrane filter holders was achieved by using one Nash Hytor 2 h.p. pump connected to a common manifold. Air flow rates were measured by using Rotameter flow-meters in series with the sampling heads. Flow rates between 11 and 20 litres/min were used. Different combinations of flow rate and nozzle size were used so that the air intake velocity was as close as possible to the wind speed in an attempt to achieve isokinetic sampling. Samples were taken at the rate of one per instrument at every main synoptic hour, i.e. 00, 06, 12, 18 GMT.

Analysis was achieved by adding a small fixed quantity of distilled water to each dish and subsequently analysing the solution for sodium content. This was achieved with an Instrumentation Laboratory IL-143-03 flame photometer which has an internal standard and is capable of an actual rate of analysis of 150 samples per hour. Sampling times varied between 1 to 2 hours in winds above 8 m s^{-1} to several hours in very light wind conditions when the total sea-salt concentration often fell to 5 μg m^{-3}. In these circumstances the sample was often of the same order as background contamination. Background sodium contamination was determined for a number of different filter types. Results are shown in Table 1. Nuclepore filters were mainly used but even with a nuclepore filter and a sample time of 2 hours, in light wind conditions the sample collected could be of the same order as the background contamination. On the other hand, accidental handling or splashing from sea water could result in the sample being very much less than background contamination. The effect of experimental errors are discussed in the author's full account of this study (Lovett, 1975).

In practice, attempts to obtain sea-salt concentration measurements as a function of height were difficult to achieve. These heights can only be considered approximate due to the motion of the ships. At gale force winds the ships often rolled by 30° from the vertical and moved through a vertical distance of several metres. In practice, in rough seas, all sampling positions could move effectively through a vertical height range of 10 metres or more.

When the ship was stopped there was apparently

Table 1. *Typical sodium content and composition of membrane filters. (Sodium content is expressed as weight in μg equivalent of NaCl)*

Type	Filter material	Sodium content (μg)
Millipore AA	Cellulose acetate and cellulose nitrate	30
Millipore HA	Cellulose acetate and cellulose nitrate (hydrophobic)	10
Millipore FH	PTFE (hydrophobic) bonded to polyethylene net	3
Gelman-Hawksley AN 800	Copolymer of acrylonitrile and PVC on nylon substrate	100
Gelman-Hawksley DM 800	Copolymer of acrylonitrile and PVC (hydrophobic)	100
Nuclepore	Polycarbonate plastic film	3
Sartorius 11104	Cellulose acetate	20

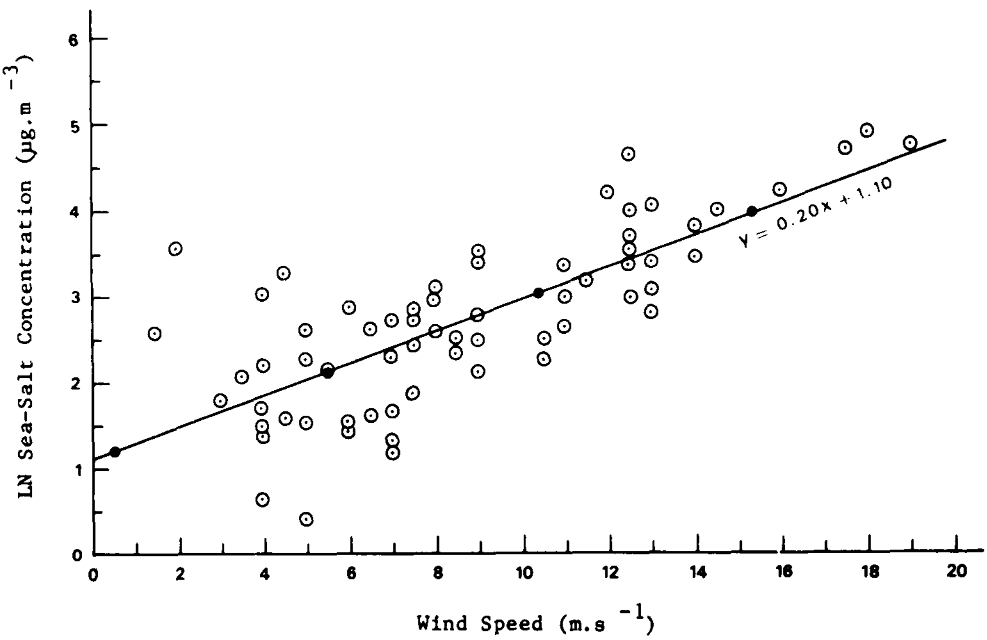

Fig. 2. Examples of total sea-salt concentration plotted as a function of wind speed. Samples were taken at Station India at a height of 15 metres asl in April 1975.

little ship-induced foam and spray. Up to wind speeds of around 13 m s^{-1} a few waves would appear to break around the stern as a result of the hull shape but there would be none at the midships position where the sampling sites were located. At wind speeds in excess of 15 m s^{-1} sampling could often only be achieved at the 15-metre site as occasionally waves would break over the side and swamp the instruments. The comparative lack of waves breaking against the ships up to quite high wind speeds is a factor in favour of weather ships in comparison with fixed platforms which could cause a significant source of sea-salt aerosol due to breaking waves. The weather ships, on the other hand, when they are stopped, behave rather like bobbing corks and most of the wave energy is used in moving the ship vertically, whereas a fixed platform can be compared to a sea-shore where breaking waves are a considerable source of sea-salt aerosol.

3. Results

A typical plot of results is shown in Fig. 2 with a least squares straight line of the form $\ln \theta = au + b$. A total of 31 similar graphs were obtained over a period of 11 months. Mean weighted values of a and b were calculated for all heights for each station and for all heights at both stations by using a weighting $w = n$ where n is the number of data points. The corresponding equations are:

Station India	5 m	$\ln \theta = 0.19u + 0.71$	(0.06)	(0.9)
	10 m	$\ln \theta = 0.13u + 1.54$	(0.07)	(0.9)
	15 m	$\ln \theta = 0.16u + 1.61$	(0.08)	(1.0)
Station Juliet	5 m	$\ln \theta = 0.17u + 1.52$	(0.06)	(0.9)
	10 m	$\ln \theta = 0.14u + 1.42$	(0.05)	(0.4)
	15 m	$\ln \theta = 0.19u + 1.03$	(0.03)	(0.5)

Standard deviations of a and b are shown in brackets after their respective mean equations.

Station India, all heights	$\ln \theta = 0.16u + 1.51$	(0.07)	(0.9)
Station Juliet, all heights	$\ln \theta = 0.17u + 1.35$	(0.05)	(0.7)
Both stations, all heights	$\ln \theta = 0.16u + 1.45$	(0.06)	(0.8)

Sampling at station Lima from ship Weather Surveyor was only undertaken at one site at 7.5 metres a.s.l. for one voyage (WS104) using three sets of instruments (denoted A, B, C). The corresponding equations are:

Station Lima	A	$\ln \theta = 0.22u + 0.20$
	B	$\ln \theta = 0.22u + 0.44$
	C	$\ln \theta = 0.25u + 0.23$

95% confidence intervals of "a" for these equations were 0.05, 0.04 and 0.04 respectively. It will be noted that these equations have a greater slope and a smaller intercept than equations for stations I and J. This can be explained by the rather different weather condition experienced at station Lima during this one voyage. The voyage was characterized by long periods of very light winds when the total sea-salt concentration fell to very low values, sometimes as low as 1 $\mu g\ m^{-3}$. This is shown on an extract from the time plot obtained from this voyage. On the other hand there was a paucity of data above 12 $m\ s^{-1}$. The very low sea-salt concentration at low wind speed resulted in a rather steeper regression line with an intercept closer to the origin. Values of θ obtained from this equation for various wind speeds are all lower than those obtained from stations I and J where low wind speeds were much less frequent.

Thus it would appear that the regression line obtained from plotting $\ln \theta$ and u is dependent also on the time variation of the wind speed.

4. Discussion of results

4.1. *Total sea-salt concentration*

This type of measurement, relying solely on quantitative measurement of small amounts of a very common element, viz. sodium, is naturally subject to large errors. It was found that by carrying out replicate sampling runs, large errors due to accidental salt contamination were possible, but by taking statistical mean values of a large number of a set of data the effect of errors could be reduced to reasonable limits. An example of replicate sampling runs from voyage WS104 is shown in Fig. 3. Meteorological data in the form of wind speed, present weather, low cloud type and depth of the lowermost mixed layer (metres) are also plotted and their influence on residence times will be discussed. No significant variation in height of sea-salt concentration was indicated as variations between correlation lines for differing sampling heights were within the range of scatter shown in Fig. 3. The mean slope of 0.16 of the regression line for the data compares with slopes of 0.16 and 0.12 for Woodcock's (1953) and Toba's (1965) data respectively. Toba's result, however, is for the production rate at the sea surface rather than sea-salt concentration at a height above sea level.

The high degree of scatter of the data points and the consequent variation in the regression lines can probably be attributed to several reasons. Sea-salt concentrations are not only a function of wind speed but of the previous wind. Another factor is that there are more data points for the lower wind range than the higher range which in the absence of a suitable weighting factor results in the regression line being more influenced by low wind speed results than high wind speed results.

The mean regression line for all data, $\ln \theta = 0.16u + 1.45$, gives values of $\ln \theta = 2.25$ ($\theta = 9.5\ \mu g\ m^{-3}$), $\ln \theta = 3.01$ ($\theta = 20\ \mu g\ m^{-3}$) and $\ln \theta = 4.01$ ($\theta = 55\ \mu g\ m^{-3}$) for wind speeds of 5 $m\ s^{-1}$, 10 $m\ s^{-1}$ and 15 $m\ s^{-1}$ respectively. These values show good agreement with mean values of $\ln \theta$ from voyages with the lowest 95% confidence intervals of ± 0.3 (WM105 and WM106). Using 95% confidence intervals of 0.3 with values of $\ln \theta$

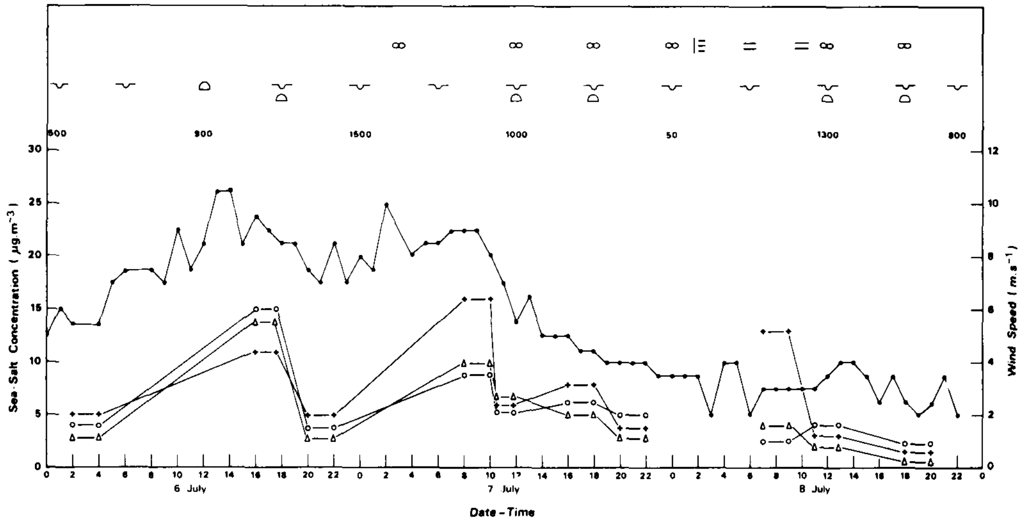

Fig. 3. Results of replicate sampling using three identical sampling heads at a height of 7.5 metres. The plotted parameters are (from the top) haze (∞), fog (|≡), mist (=), stratocumulus (⁓), and cumulus (⌓). Below that the height of the lowest mixed layer (in metres) is given. Full circles represent wind speed and the aerosol samples are represented by plus, circles and triangles.

from the regression line equation give ranges of values of θ of 7–13 at 5 m s^{-1} and of 15–27 and 40–74 for wind speeds of 10 m s^{-1} and 15 m s^{-1} respectively. These results are slightly higher than, but of the same order as, cloud base measurements made by Woodcock (1953) and are also in good agreement with results of Monahan (1968) and Blanchard and Syzdek (1972). They are however less than the results of Tsunogai et al. (1972) by a factor of about 10.

4.2. *Residence time of sea-salt particles*

The analysis of total sea-salt concentration as a function of time indicated the response to wind speed variation of sea-salt concentrations. With increases in wind speed, increases in sea-salt concentrations were simultaneous. With decreases in wind speed, the decrease in sea-salt concentrations was not simultaneous due to the residence time of sea-salt particles. The time taken for sea-salt concentrations to fall to very low values during prolonged periods of low wind speed should be an indication of the residence times of sea-salt particles. Fig. 3, which is an example of a time plot, shows such a prolonged period (6 to 12 hours) of winds less than 3 m s^{-1} when the sea-salt concentration fell to around 1 μg m^{-3}. These low concentrations, which were confirmed by results of replicate sampling, tend to confirm the suggestion that fallout is the more important mechanism for larger particles. The residence times indicated by Fig. 3 agree with Eriksson's and Toba's theoretical values for larger particles (i.e. 6 to 12 hours for particles $>10^{-9}$ g). It is possible that residence times of particles are dependent on wind speed or turbulence. Hall (1975), however, suggests that turbulence does not have an appreciable effect on residence times as turbulence is probably equally effective in depositing particles back into the sea as it is in keeping particles airborne.

4.3. *Effects other than wind speed*

Attempts were made to identify and quantify the effect of other meteorological parameters (e.g. conditions of low relative humidity would be expected to be asociated with higher sea-salt concentrations than high relative humidity conditions). However no significant correlation was observed. The depth of the lowermost mixed layer, obtained from tephigrams, and the amount and type of low cloud were also plotted in Fig. 3 in an attempt to observe any possible effect due to convection but again no significant correlation was found.

Relative humidity and turbulence have been identified by Eriksson (1959) and Toba (1965) as the most important meteorological parameters affecting sea-salt concentrations apart from wind speed. Failure to identify these effects would indicate that the investigation of other factors would be as inconclusive. It is possible that real scatter of results is due to sea-salt particles existing in discrete air parcels. Toba (1965) has suggested that sea-salt particles could exist in air parcels of quite high concentrations which drift about in the atmosphere and do not mix with air with a low sea-salt concentration. This seems unlikely as air exhibits a well-mixed nature with respect to other parameters (e.g. humidity). Another factor which to some extent explains any real scatter of results is the technique for wind measurement. These were obtained by observation of anemometer readings at hourly intervals. Different observers give different interpretations to fluctuating anemometer needles and the recorded wind speeds are mean speeds and give no indication of the size of gusts. Measurements were taken over the course of a year and no seasonal variation could be detected. It also appears that the sea surface temperature is not significant as the SST's encountered (10–15 °C) were much lower than those near Hawaii (20–25 °C) but sea-salt concentrations were similar (Woodcock, 1953).

5. Acknowledgements

The author, who is a Lieutenant Commander in the Royal Navy, acknowledges with gratitude the help given by the Director of Naval Oceanography and Meteorology, Ministry of Defence, London, and by Professor T. D. Patten, Director, Institute of Offshore Engineering, Heriot-Watt University. He is particularly grateful to the Marine Superintendent, Meteorological Office, for being allowed use of the weather ships and to the officers and men of the ships who so willingly co-operated in this project. Valuable assistance was also given by Dr. K. Weston, Department of Meteorology, Edinburgh University, and by Mr. A. N. Dickson, Department of Mechanical Engineering, Heriot-Watt University.

REFERENCES

Blanchard, D. C. and Syzdek, L. 1972. Variations in Aitken and Giant Nuclei in marine air. *J. Phys. Oceangr. 2*, 255–262.

Durbin, W. G. and White, G. D. 1961. Measurement of the vertical distribution of atmospheric chloride particles. *Tellus 13*, 500–273.

Eriksson, E. 1959. The yearly circulation of chloride and sulphur in nature; meteorological, geochemical, and pedological implications. Part 1. *Tellus 11*, 375–403.

Hall, C. D. 1975. The simulation of particle motion in the atmosphere by a numerical random walk model. *Quart. J. Royal Met. Soc. 101*, No. 428, 235.

Junge, C. E. 1972. Our knowledge of the physico-chemistry of aerosols in the undisturbed marine environment. *J. Geophys. Res. 77*, 5183–5200.

Lovett, R. F. 1975. The occurrence of airborne sea-salt and its meteorological dependence. M.Sc. thesis, Heriot-Watt University, Edinburgh.

Mohahan, E. C. 1968. Sea spray as a function of low elevation wind speed. *J. Geophys. Res. 73*, 1127–1137.

Toba, Y. 1961. Drop production by bursting of air bubbles on the sea surface. III. Study by use of a wind flume. *Mem. Coll. Sci. Kyoto Univ.* Series A, Col. 29, No. 3 Art. 4, 313.

Toba, Y. 1965. On the giant sea-salt particles in the atmosphere. I. General features of the distribution. *Tellus 17*, 131–145.

Toba, Y. 1965b. On the giant sea-salt particles in the atmosphere. II. Theory of the vertical distribution in the 10 m layer over the ocean. *Tellus 17*, 365–382.

Tsunogai, S., Saito, O., Yamada, K. and Nakaya, S. 1972. Chemical composition of oceanic aerosol. *J. Geophys. Res. 77*, 5283–5292.

Woodcock, A. H. 1953. Salt nuclei in marine air as a function of altitude and wind force. *J. Meteorol. 10*, 362–371.

Woodcock, A. H. 1957. Atmospheric sea-salt nuclei data for Project Shower. *Tellus 9*, 521–527.

This paper is published with the permission of the Ministry of Defence, London.

КОЛИЧЕСТВЕННЫЕ ИЗМЕРЕНИЯ МОРСКИХ СОЛЕЙ В ВОЗДУХЕ СЕВЕРНОЙ АТЛАНТИКЕ

В период с сентября 1974 г. по июль 1975 гг. в 11 рейсах судов погоды в Северной Атлантике были проведены измерения концентраций морских солей в воздухе. Полные концентрации морских солей были измерены в пробах воздуха с помощью мембранных фильтров. Забор проб производился на уровнях 5, 10 и 15 метров над уровнем моря. Всего была взята 1821 проба со средним количеством проб 57 в каждом месте на рейс.

Была сделана попытка прокоррелировать концентрации солей со скоростями ветра и другими метеорологическими факторами. Было найдено, что полная концентрация морской соли может быть представлена как функция скорости ветра уравнением $\ln \theta = 0{,}16u + 1{,}45$ (θ = концентрация солей в мгм$^{-3}$, u = скорость ветра в мс$^{-1}$). Это указывает на хорошее согласие с результатами Бланшара и Сиздека. Величины временных вариаций концентраций солей и скоростей ветра дают возможность оценить время жизни солей в воздухе от 12 до 24 часов. Попытки выделить зависимости от других метеорологических параметров не были определенными.